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13. ABSTRACT *(Maximum 200 words)*

The project involved an experimental investigation of the synthesis and the electrical transport properties of semimetal-semiconductor based heterostructures and devices. The structures consisted of elemental (Sb) semimetals in combination with antimonide based III-V semiconductors (GaSb). The investigation of these novel semimetal-semiconductor heterostructures was motivated by their unique electronic properties and potential device applications, including high conductivity interconnects, double-barrier semimetal-base resonant tunneling transistors, and nanostructures operating in the mesoscopic regime. The structures were synthesized using molecular beam epitaxy, and their structural and electrical transport properties were investigated. In addition to substantially enhanced understanding of this materials combination the project resulted in the demonstration of double barrier Sb/GaSb resonant tunneling structures exhibiting negative differential resistances and Sb submicron loops displaying Aharonov-Bohm oscillations.

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ELECTRONIC PROPERTIES OF SEMIMETAL-SEMICONDUCTOR (V/III-V) HETEROSTRUCTURES AND DEVICES

FINAL REPORT

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August 1, 1997

US Army Research Office

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University of Houston

A. Statement of Problem studied

The project involved an experimental investigation of the synthesis and the electrical transport properties of semimetal-semiconductor based heterostructures and devices. The structures consisted of elemental (Sb) semimetals in combination with antimonide based III-V semiconductors (GaSb). The investigation of these novel semimetal-semiconductor heterostructures was motivated by their unique electronic properties and potential device applications, including high conductivity interconnects, double-barrier semimetal-base resonant tunneling transistors, and nanostructures operating in the mesoscopic regime. The structures were synthesized using molecular beam epitaxy, and their structural and electrical transport properties were investigated. In addition to substantially enhanced understanding of this materials combination the project resulted in the demonstration of double barrier Sb/GaSb resonant tunneling structures exhibiting negative differential resistances and Sb submicron loops displaying Aharonov-Bohm oscillations.

B. Summary of important results

Transport

Full details are contained within the publications listed. Mobilities in GaSb/Sb superlattices with period thickness ranging from 50Å - 300Å were determined. Figure 1 shows electron and hole mobilities for a 14-period superlattice (30Å/20Å), in which the carrier concentrations are only slightly lower than those in bulk Sb. That both m_n and m_p exceed

$2000 cm^2/v.s$ in a sample having two interfaces every 50Å indicates that boundary scattering must far weaker than in most thin heterostructures combining materials with different crystal structures. Similar electron and hole mobilities were measured for a 37-period superlattice with somewhat thicker Sb layers (60Å/20Å).

Vertical I-V transport results on a nominal 35Å/50Å/35Å GaSb/Sb/GaSb double-barrier resonant tunneling diode structure are shown in Figure 2. The differential current with respect to voltage is calculated and plotted. The peak appears at 4.0 eV, and negative differential resistance occurs around this region. The voltage across the active resonant tunneling structure should be lower than this value, because of voltage drops across the depletion, accumulation and buffer regions in the emitter and collect layers adjacent to the DBRT. Large value of current are due to imperfect junction leakage and hot electron or hole. Negative differential resistance occurs at both positive and negative bias voltage with symmetric characteristics.

Sb based submicron structures were fabricated using ion beam milling techniques. Aharonov-Bohm effects were studied in a 1μm diameter Sb loop. Variation of the sample resistance as a function of magnetic field is shown in the inlet of Figure 3. A Fourier transform analysis was performed to extract the amplitude of the oscillating component. A peak is observed near $7.5x10^{-3}$ G^{-1}, which corresponds to an oscillation period of B_0=133.1 G. The theoretical period for Aharonov-Bohm oscillations is given by B_0=h/eA, where A is the area enclosed by the two paths. For our device the minimum loop area is 0.4x0.4 mm^2 and the maximum loop area is 0.4x0.4 mm^2 giving a range at 113 $<B_0<$250 Gauss.

Different regions of the magneto-resistance data were Fourier transformed independently, the results giving shown in Figure 4. All regions had the same number of data points. The peak at 0.0753 G^{-1} exists in all regions, with nearly the same a oscillation amplitude. A Fourier transform analysis was also performed on the curve of resistance vs. reciprocal magnetic field, in order to examine whether the oscillation was caused by the Shubnikov-de Haas (SdH) effect. No peak was found near 100G, where SdH oscillation should appear confirming the osscillations to be AB.

Theory

Extensive theoretical work was conducted to determine electronic and optical properties of Sb/GaSb superlattices. We were particularly interested in the metal-insulator transition. The detailed results for the electronic structures of Sb/Ga(Al)Sb (111) semimetal-semiconductor superlattices were studied within a tight-binding theory with spin-orbit interaction. In order to perform the band structure calculations, we obtained tight-binding parameters for bulk GaSb, AlSb, and Sb by fitting the first principle and experimental results. Due to the strong confinement effect, an indirect narrow gap appears in these materials with thin antimony layers. With increasing the thickness of the Sb layer, a possible semiconductor-semimetal transition is suggested at a certain thickness. By varying different interface relaxation and offsets, we confirm that the interface states which are localized near the interface do not prevent the formation of the band gap in Sb/Ga(Al)Sb superlattices. In many ways, we have proposed and theoretically studied a new kind of narrow-gap materials which possess strong optical nonlinearity in the infrared.

Summary

We have performed a comprehensive program into the synthesis of Sb/GaSb heterostructures and multilayers using molecule beam epitaxy (MBE), as well as fabrication of Sb-based nanostructures using ion-beam patterning. Transport results display negative differential resistance (NDR) in double barrier Sb/GaSb resonant tunneling structures and Aharonov-Bohm oscillations in Sb submicron loops. The results demonstrated the viability of integration of Sb layers with the III-V semiconductor family, and have demonstrated the viability of such heterostructures in new electronic and opto-electronic devices. Full details of which are available in the related publications.

C. List of Publications

E.G. Wang, J.H. Xu, W.P. Su and C.S. Ting "Enhancement of optical absorption by disorder in three-dimensional superlattices" *Appl. Phys. Lett* **64** 443 (1994)

E.G. Wang, J.H. Xu, W.P. Su and C.S. Ting "Electronic structure of Sb/Ga(Al)Sb (111) semimetal-semiconductor superlattices", *J. Appl. Phys.* **76** 5318 (1994)

E.G. Wang and C.S. Ting "Electronic structure and optical properties of (ZnS)n/(Si2)m superlattices" *Phys. Rev.* **B51** 9791 (1995)

E.G. Wang and C.S. Ting "Optical epilayers on silicon substrate: Electronic and optical properties of ZnS/Si superlattices" *J. Appl. Phys.* **77** 4107 (1995)

E.G. Wang and C.S. Ting "Indirect to direct band gap transition and enhanced optical absorption of GaP/AlP random superlattices" *Appl. Phys. Lett.* **66** 1400 (1995)

E.G. Wang, C. Chen and C.S. Ting " Tight-binding calculation of ZnSe/Ge superlattice: electron structure and optical properties" *J. Appl. Phys.* **78** 1832 (1995)

E.G. Wang, Y. Zhou, C.S. Ting, J. Zhang, T. Pang and C. Chen "Excitons in spatially separated electron-hole system: A quantum Monte-Carlo study" *J. Appl. Phys.* **78** 7099 (1995)

Y.M. Gu, E.G. Wang, C.S. Ting and L. Kleinman "First principle study of the quaternary semiconductor superlattices GaX/YAs (X=N,P; Y=Al, In)" *Phys. Rev.* **B54** 13784 (1996)

T.D. Golding, J.A. Dura, W.C. Wang, J.T. Zborowski, A. Vigliante, J.H. Miller Jr. and J. R. Meyer. "Investigation of Sb/GaSb multilayer structures for potential application as a narrow bandgap system". *Semicond. Sci. Technol.* **8** S117-S120 (1993).

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W.C. Wang, J.A. Dura, J.T. Zborowski, A. Vigliante, H.C. Chen, and T.D. Golding. "Preparation of Sb/GaSb {111}-oriented multilayer structures using molecular beam epitaxy and migration enhanced epitaxy". *J. Vac. Sci. Technol.* **A11**, 1001 (1993).

A. Vigliante, S.C. Moss, J.A. Dura, W.C. Wang, and T.D. Golding. "X-ray studies of Sb/GaSb heterojunction and multilayer structures: A new semimetal/semiconductor system". *Mat. Res. Soc. Symp. Proc.* **281**, 721 (1993).

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J.R. Meyer, C.A. Hoffman, T.D. Golding, J.T. Zborowski, A. Vigliante,High speed electronic devices based on integration of Sb with InAs/GaSb/AlSb family heterostructures. *Proc. 22nd Int. Conf. on Physics of Semiconductors, Vancover,* p1612, (1994)

J.A. Dura, A. Vigliante. T.D. Golding, S. C. Moss, "Epitaxial growth of Sb/GaSb structures: An example of V/III-V Heteroepitaxy". *J. Appl. Phys.* **77** (1) 21-27 (1995).

T.D. Golding, J.R. Meyer, J. Huang, C.A. Hoffman, E.G. Wang, J.H. Xu, and J.T. Zborowski, "Electronic devices based on III-V/V heterostructures". *Inst. of Phys., Proc. 7th Int. Conf. on Narrow Gap Semiconductors,* (1995)

T.P. Hogan, T.D. Golding, J. Huang, and J.H. Miller, Jr., "Growth, Patterning and Characterization of Mixed structure Sb/GaSb Heterostructures and Multilayers", *Material Research Society Spring Meeting* (www.mrs.org)**B5.42** (1997).

J. Huang, T.D. Golding, T. Hogan. D.P. Stumbo, J.C. Wolfe, J.R. Meyer and C.A. Hoffman, "Fabrication and transport properties of Sb/GaSb multilayers and nanostructures" *to be published Appl. Phys. Lett* (1997)

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Dr. Mirim Lee Dept. of Physics & TCSUH(Ting)

Dr. J. A. Dura, Dept. of Physics, (Golding)

Graduate Students

Dr. J. Huang, Dept. of Physics (now at Texas Instruments, Dallas, Texas). Dr Huang conducted his Ph.D dissertation on this project.

Dr. A. Vigliante, Dept. of Physics, (now at Brookhaven national Laboratory). A significant portion of Dr. Vigliante Ph.D dissertation was based on this project.

Dr. J. T. Zborowski, Dept. of Physics, (now at GEM Research, Houston). A significant portion of Dr. Vigliante Ph.D dissertation was based on this project.

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Inventions

Semimetal-Semiconductor Heterostructures and Multilayers
Issued 1995, U.S. Patent No. 5,449,561.

Optical Switches and Detectors Utilizing Indirect Narrow-Gap Superlattices as the Optical Materials
Issued 1995. U.S. Patent No. 5,477,377.

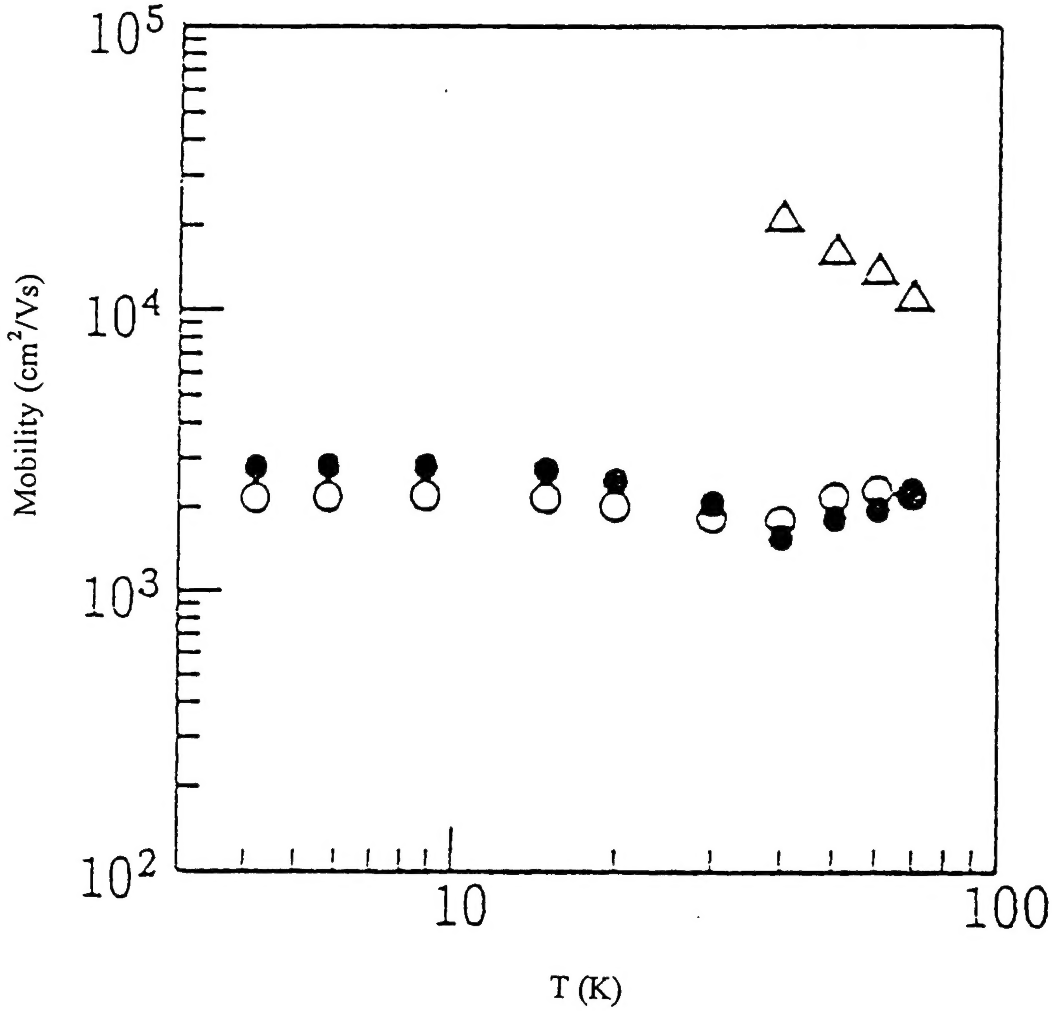

Figure 1: Electron (Filled circles) and hole (open circles) mobilities for a 14-period nominal 30Å/20Å Sb/GaSb superlattice verses temperature. Substrate hole mobilities (triangles) are also shown.

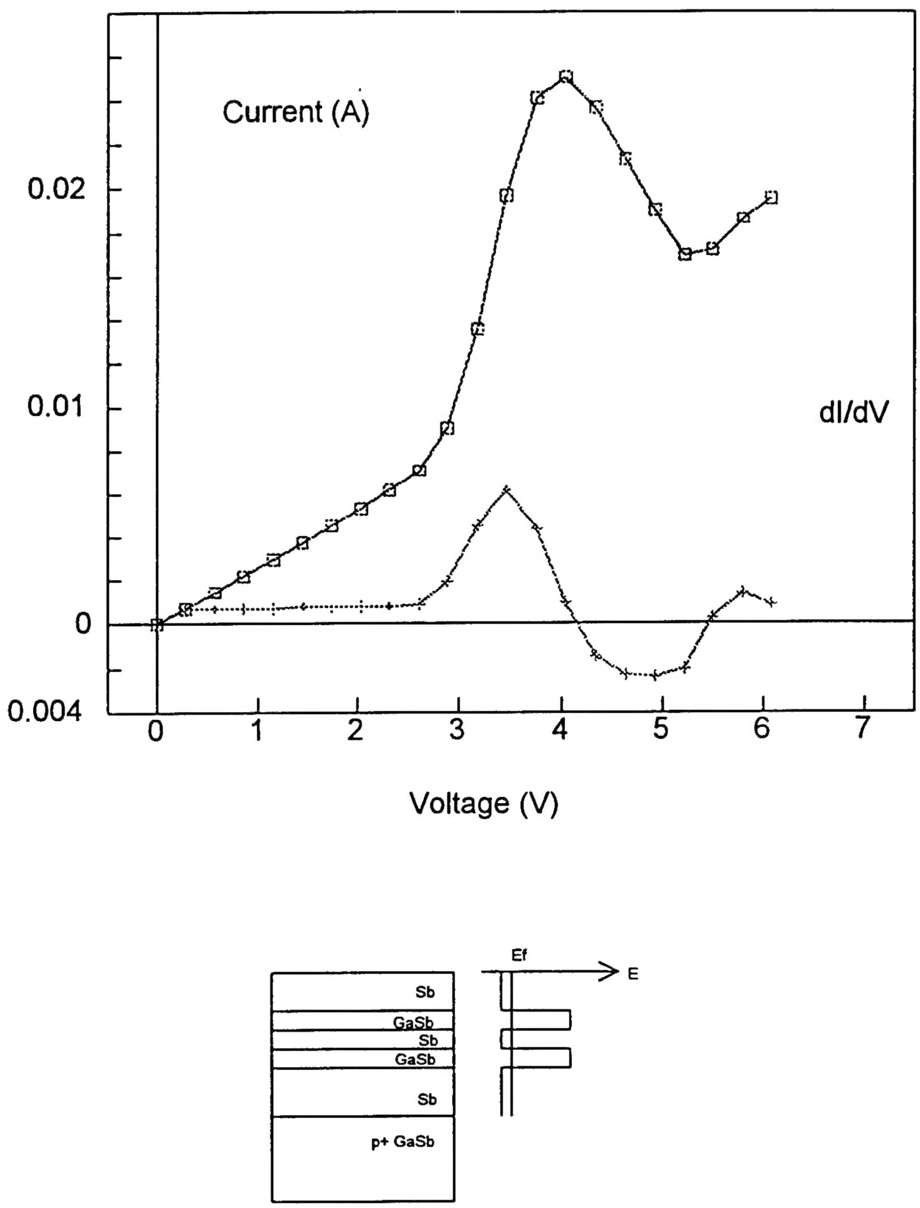

Figure 2. Vertical I-V characteristics for a nominal 35Å/50Å/35Å GaSb/Sb/GaSb double barrier resonant tunneling diode at 77K

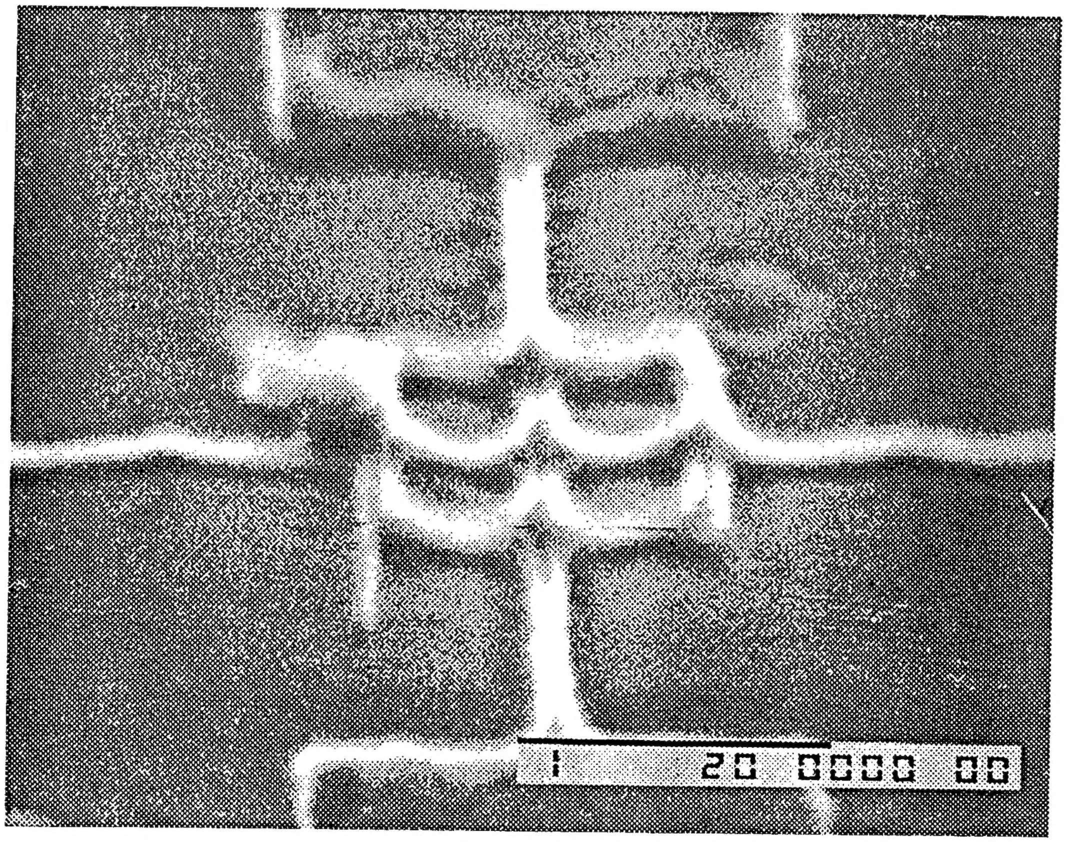

Figure 3: Micrograph of a 2x2 Sb loop array, on GaSb(111). The linewidth of the structure is approx 1000Å.

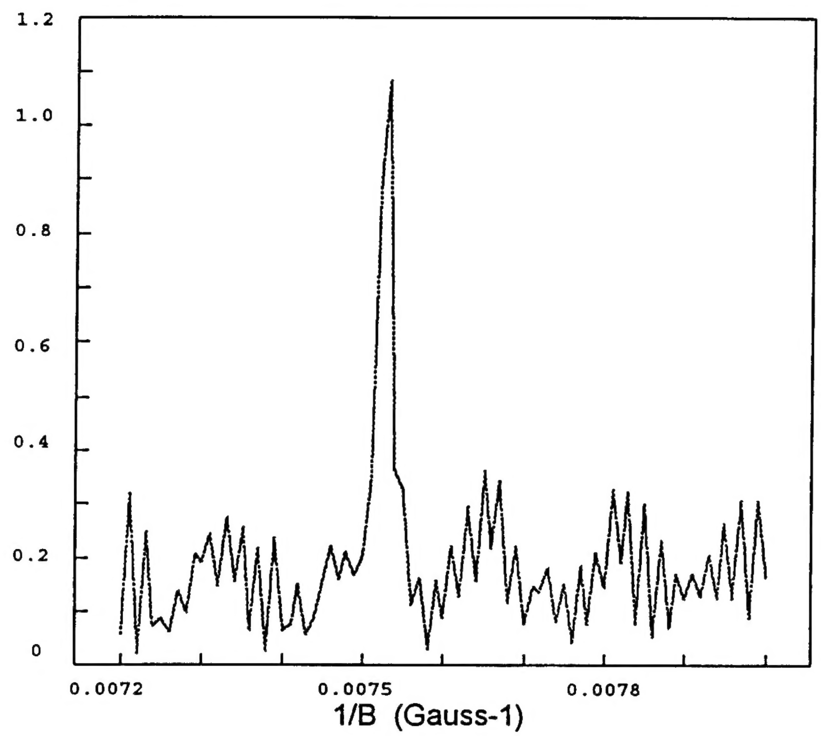

Figure 4: Fourier Transform of Magnetrospectra for a 1x1 loop showing frequency consistent with area of loop.